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지반-구조물 상호작용계의 경계면에서 미끄러짐과 분리현상을 고려한 이차원 지하구조물의 비선형 지진응답해석

Nonlinear Earthquake Response Analysis of 2-D Underground Structures with Soil-Structure Interaction Including Separation and Sliding at Interface

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ABSTRACT

The paper presents an effective analytical method for SSI systems which can have separation or sliding at the soil-structure interface. The method is based on a hybrid approach which combines a linear SSI code KIESSI-2D in frequency domain with a commercial finite element package ANSYS to obtain nonlinear dynamic responses in time domain. The method is applied to a 2-D underground box structure which experiences separation and sliding at the soil-structure interface. Material nonlinearity of the concrete structure is also included in the analysis. Effects of the interface conditions are examined and some critical factors affecting the seismic performance of underground structures are identified.

1. INTRODUCTION

In actual soil-structure interaction (SSI) systems, the separation at the soil-structure interface is frequently observed during strong earthquake events. The behavior results in increase of contact stresses since the seismic load is transmitted through the reduced contact area. In addition, sliding along the interface may also occur during strong earthquakes. Thus the response of the SSI system can be significantly influenced by the interface conditions such as separation and sliding(1). However, most studies concerned with SSI to date have assumed a perfect bond at the soil-structure interface because analytical tools of these studies are usually formulated in frequency domain. The paper presents an effective analytical method for a realistic response analysis of SSI systems in which separation and/or sliding can take place at the soil-structure interface and the structure manifests material nonlinear. The method is based on a hybrid approach which combines a linear SSI code KIESSI-2D in frequency domain developed by the third author with a commercial finite element package ANSYS in order to consider nonlinear dynamic responses in time domain. The method is applied to a dynamic analysis of a 2-D underground box structure subjected to a strong earthquake. Nonlinear time varying interface conditions and material nonlinearity of the concrete material are included in the analysis. Effects of the interface conditions are examined, and some important features affecting the seismic performance of the underground

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structure are discussed.

2. KIESSI-2D MOTHODOLOGY FOR LINEAR SSI ANALYSIS

For a soil-structure interaction system, representation of the frequency-dependent characteristic of the system due to the unbounded nature of the far field soil medium is of utmost importance. In this study, the 2-D finite element model incorporating infinite element formulation is utilized as depicted Fig. 1. The structure and near field soil region are modeled with the standard plain strain finite elements, *whereas the far field soil is* represented using dynamic infinite elements placed along the interface between the near and far field regions.

Referring to the schematic representation shown in Fig. 1, earthquake responses can be computed by solving the following wave radiation equation

$$\begin{bmatrix} \mathbf{S}_{nn}(\omega) & \mathbf{S}_{ni}(\omega) \\ \mathbf{S}_{in}(\omega) & \mathbf{S}_{ii}(\omega)+\tilde{\mathbf{S}}_{ii}(\omega) \end{bmatrix} \begin{Bmatrix} \mathbf{u}_n(\omega) \\ \mathbf{u}_i(\omega) \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{p}_i^f(\omega) \end{Bmatrix} \tag{1}$$

in which $\mathbf{u}(\omega)$ is the total displacement vector with respect to a fix point in space ; $\mathbf{S}(\omega)$ is the dynamic *stiffness matrix obtained by the finite element formulation for the near field;* $\tilde{\mathbf{S}}(\omega)$ *is the impedance matrix computed by the infinite element formulation for the far field region* ; the subscripts n denotes the degrees of freedom in the near field including the structure and the soil ; the subscript i represents those along the interface between the near and the far field regions ; and $\mathbf{p}_i^f(\omega)$ is the equivalent earthquake force along the interface (Γ_i), as shown in Fig. 1, which can be calculated from the free-field responses as

$$\mathbf{p}_i^f(\omega) = \tilde{\mathbf{S}}_{ii}(\omega)\mathbf{u}_i^f(\omega) - \mathbf{A}\mathbf{t}_i^f(\omega) \tag{2}$$

where $\mathbf{u}_i^f$ and $\mathbf{t}_i^f$ are the displacement and the traction on Γ_i obtained from the equivalent linear free-field soil system, and $\mathbf{A}$ is a constant transformation matrix.

The present rigid exterior boundary method appears to be quite attractive for the equivalent linear analysis of SSI systems since the total displacement of the heterogeneous nonlinear soil region (near field) can be obtained directly. Accordingly, the shear strain in the soil region may be directly evaluated and used for updating the shear moduli and the hysteretic damping ratios. The impedance matrix of the far-field, $\tilde{\mathbf{S}}_{ii}(\omega)$ can be computed by assembling the element matrices of the infinite elements as

$$\tilde{\mathbf{S}}^{(e)}(\omega) = (1 + j2h^{(e)})\tilde{\mathbf{K}}^{(e)}(\omega) - \omega^2\tilde{\mathbf{M}}^{(e)}(\omega) \tag{3}$$

where $j = \sqrt{-1}$; $h^{(e)}$ is the hysteretic damping ratio of infinite element (e); and $\tilde{\mathbf{K}}^{(e)}(\omega)$ and $\tilde{\mathbf{M}}^{(e)}(\omega)$ are the element stiffness and mass matrices, respectively.

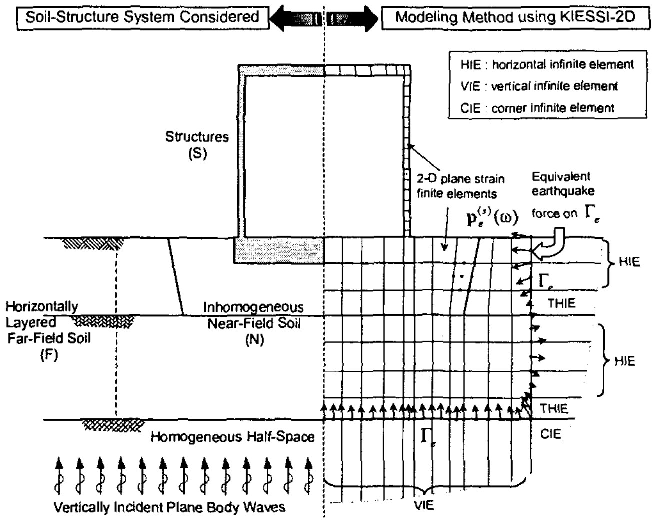


Fig. 1. Dynamic analysis using KIESSI-2D for a linear SSI problem

3. HYBRID METHOD FOR NONLINEAR SSI ANALYSIS IN TIME DOMAIN

Transforming Eq. (1) into time domain, Eq. (1) becomes:

$$\begin{bmatrix}[\mathbf{M}_{nn}] & [\mathbf{M}_{ni}]\\ [\mathbf{M}_{in}] & [\mathbf{M}_{ii}]\end{bmatrix}\begin{Bmatrix}\{\ddot{\mathbf{u}}_n(t)\}\\ \{\ddot{\mathbf{u}}_i(t)\}\end{Bmatrix}+\begin{bmatrix}[\mathbf{C}_{nn}] & [\mathbf{C}_{ni}]\\ [\mathbf{C}_{in}] & [\mathbf{C}_{ii}]\end{bmatrix}\begin{Bmatrix}\{\dot{\mathbf{u}}_n(t)\}\\ \{\dot{\mathbf{u}}_i(t)\}\end{Bmatrix}+\begin{bmatrix}[\mathbf{K}_{nn}] & [\mathbf{K}_{ni}]\\ [\mathbf{K}_{in}] & [\mathbf{K}_{ii}]\end{bmatrix}\begin{Bmatrix}\{\mathbf{u}_n(t)\}\\ \{\mathbf{u}_i(t)\}\end{Bmatrix}$$
$$+\begin{Bmatrix}\{0\}\\ \{\mathbf{r}_i(t)\}\end{Bmatrix}=\begin{Bmatrix}\{0\}\\ \{\mathbf{p}_i^f(t)\}\end{Bmatrix} \tag{4}$$

where $\{\mathbf{r}_i(t)\}$, the interaction force associated with the equivalent linear response, is expressed as:

$$\{\mathbf{r}_i(t)\}=\int_0^t[\tilde{\mathbf{S}}_{ii}(t-\tau)]\{\mathbf{u}_i(\tau)\}d\tau \tag{5}$$

From Eq. (4), the equation of motion for the near field soil and the structure excluding the interface boundary can be written as:

$$\begin{aligned}&[\mathbf{M}_{nn}]\{\ddot{\mathbf{u}}_n(t)\}+[\mathbf{C}_{nn}]\{\dot{\mathbf{u}}_n(t)\}+[\mathbf{K}_{nn}]\{\mathbf{u}_n(t)\}=\\ &\qquad -[\mathbf{M}_{ni}]\{\ddot{\mathbf{u}}_i(t)\}-[\mathbf{C}_{ni}]\{\dot{\mathbf{u}}_i(t)\}-[\mathbf{K}_{ni}]\{\mathbf{u}_i(t)\}\end{aligned} \tag{6}$$

where the term in the right-hand-side is considered as an input load into the interior nonlinear soil-structure system if responses on the interface between near field and far field, $\{\mathbf{u}_i(t)\}$, $\{\dot{\mathbf{u}}_i(t)\}$, and $\{\ddot{\mathbf{u}}_i(t)\}$, can be determined prior to the nonlinear analysis for the interior system.

In this study, the interface responses are approximately obtained through the linear SSI analysis for the whole system, in which the nonlinearities in the interior soil and the structure are accounted for using the equivalent linearization technique. At this juncture, it should be noted that the interface responses are not sensitive to the degree of nonlinearities in the interior soil or in the structural system, as long as the interface is located far enough from the nonlinear region. This approach was found to be very practical since the solution of Eq. (6) can easily be obtained utilizing a general-purpose finite element code such as DIANA, ANSYS, ABAQUS, etc(2). In this study, ANSYS program is employed for the nonlinear dynamic analysis of the soil-structure system.

4. MODELING CONTACT NONLINEARITIES

Since stress and strain in the soil can attain high values in the vicinity of the structure during the seismic excitation, the possibility of the separation and sliding between the soil and structure is most likely along the interface(1). To realistically model, the separation and sliding between the soil and structure in this study, the soil-structure interface is modeled by using contact elements (conta172) and target elements (targe169) in ANSYS program. In ANSYS, if one surface is stiffer than the other, the softer one is chosen as the contact surface whereas the stiffer one as the target surface. Accordingly, at the soil-structure interface, contact elements are employed for the soil and target elements are used for the structure as shown in Fig. 2. On the other hand, the dynamic properties governing the sliding are determined by the Mohr-Coulomb failure law at the interface.

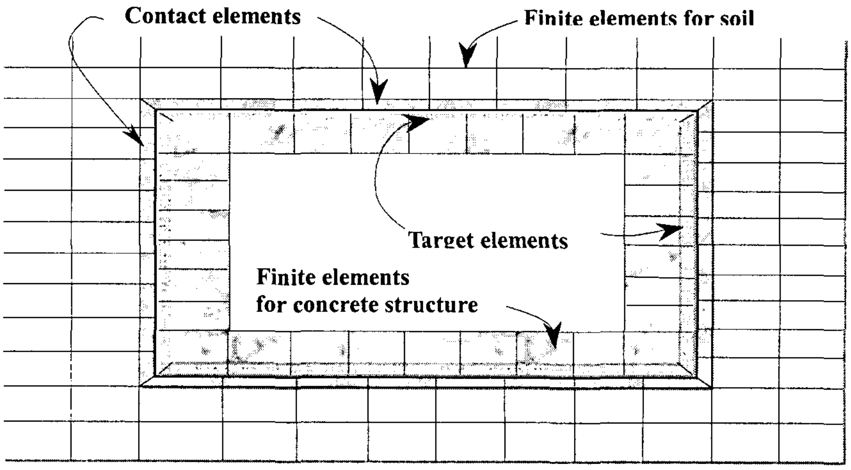


Fig. 2. Designation of contact surface and target surface

5. NONLINEAR EARTHQUAKE RESPONSE ANALYSIS

5.1 Analytical model and seismic input excitation

A nonlinear earthquake response analysis is carried out for a 2-D underground box structure which can undergo separation and sliding at the soil-structure interface. The dimension of the 2-D underground box structure, which is a typical subway tunnel in Korea, is given in Fig. 3. Fig. 4 shows its finite-infinite element mesh including 358 finite elements and 59 infinite elements for linear SSI analysis in frequency domain. The corresponding ANSYS model for nonlinear dynamic analysis in time domain, including 358 finite elements and

40 contact and target elements, is shown in Fig. 5. The material parameters are listed in Table 1

On the other hand, the Mohr-Coulomb failure law is employed in the constitutive relation of contact and target elements. The friction coefficient and maximum shear stress at interface between soil and structure are chosen to be 0.577 and 124.6 kN/m^2, respectively. Material nonlinearity is considered for the concrete structure as well as the contact and target elements in this study. For the concrete, it is assumed that the total stress range is equal to twice the yield stress, so that the Bauschinger effect is included as shown in Fig. 6(3). The seismic excitation is simulated by the control motion at ground surface of the free field soil layer. The control acceleration is given in Fig. 7, which is scaled to be 0.5g PGA using the acceleration record at ground surface of Hualien site in Taiwan on May 1, 1995(4). In the following sections, the contours of stresses and plastic strain will be discussed for two cases: (1) including both material and interface nonlinearities, and (2) including material nonlinearity only.

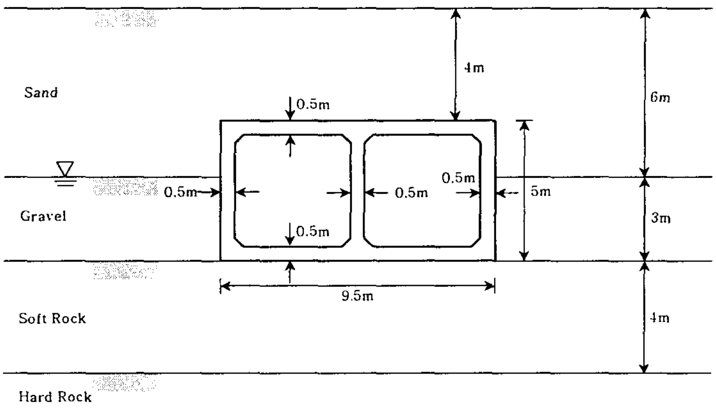


Fig. 3. 2-D underground RC box structure

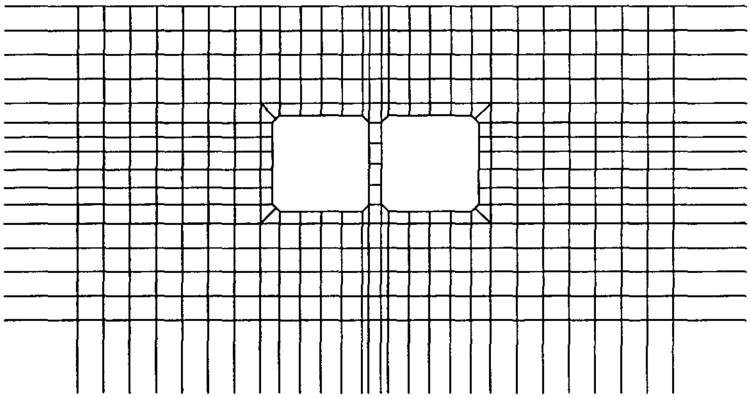


Fig. 4. KIESSI-2D model for linear SSI analysis

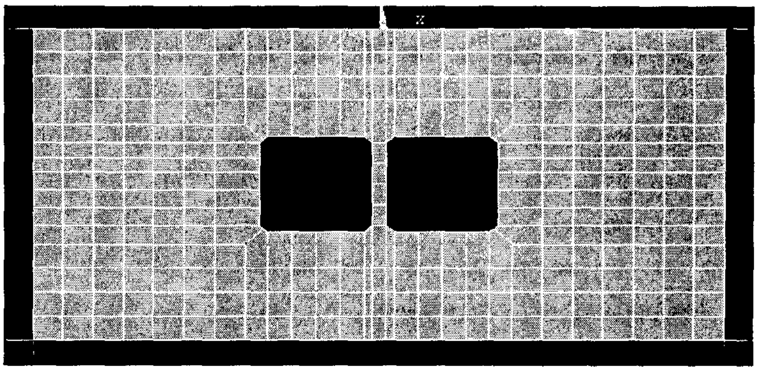


Fig. 5. ANSYS model for nonlinear dynamic analysis

Table 1. Material properties of 2-D underground box structure

Regions	Mass Density (kg/m^3)	Shear Wave Velocity (m/sec)	Poisson's Ratio (υ)	Damping Ratio (%)
Sand	1800	150	0.3	2
Gravel	2000	300	0.3	2
Soft Rock	2200	600	0.3	2
Hard Rock	2400	800	0.2	2
Concrete Box	2500	20.0 GPa	0.16	2
Concrete Column	500	4.00 GPa	0.16	2

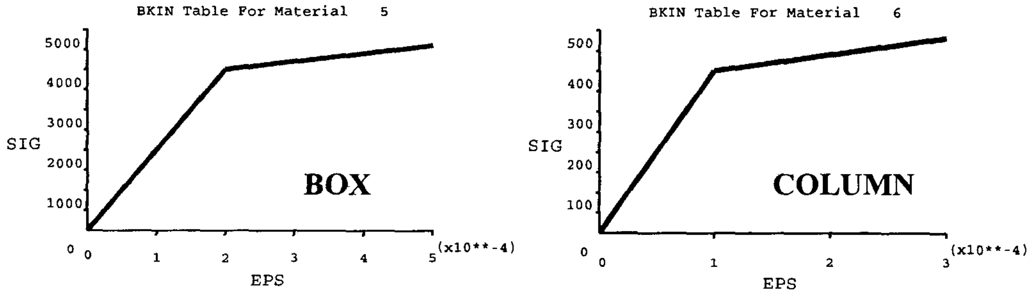


Fig. 6. Bilinear kinematic hardening for concrete

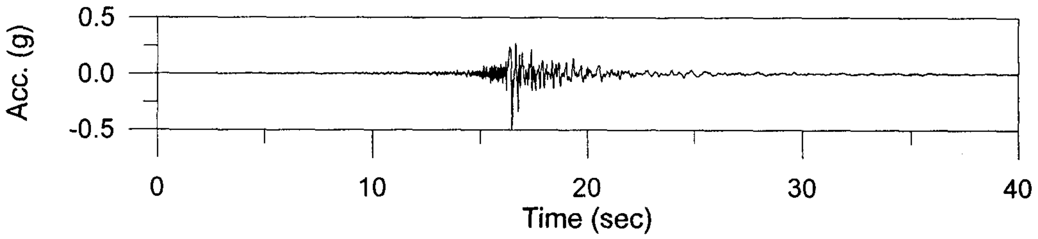
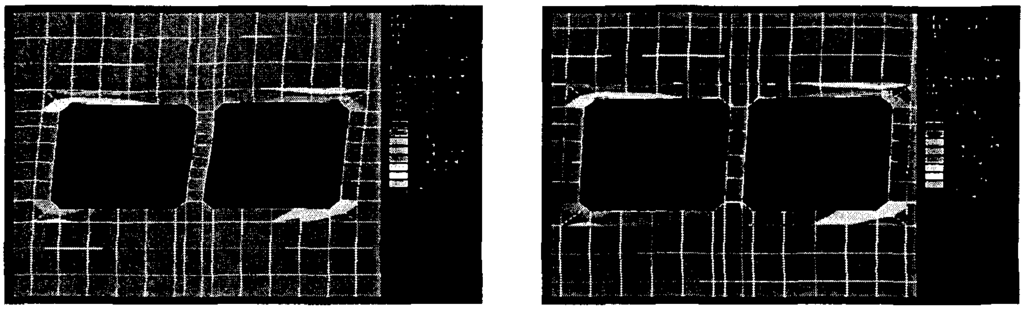


Fig. 7. Time history of input control acceleration

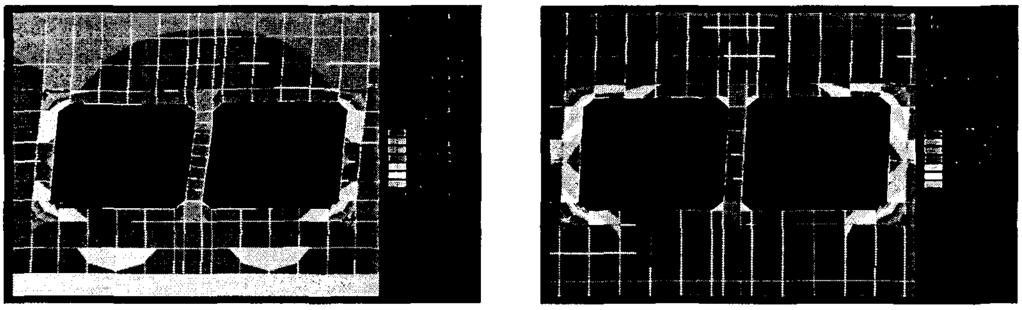
5.2 The results of nonlinear earthquake response analysis

Figs. 8 and 9 show that stress concentration in the concrete structure is quite different from the perfect-bond case due to sliding and separation on the interface. Similar trend can be found in the plastic strains of the RC column depicted in Fig. 10. The maximum stresses are reduced to about 60% of the perfect-bond case, while the maximum plastic strains to 27%. Besides, deformation of the concrete structure at the ultimate state becomes much smaller than the case with perfect-bond. The results indicate that lesser seismic load is transmitted to the structure if the separation and/or sliding take place at the interface. It is also shown that the sliding at the interface results in an increase in relative displacement and a decrease in confining pressure in the soil at the interface. In other words, dominant sliding at the interface plays the role of dissipating seismic energy. Fig. 11 shows that the separation and sliding are concentrated around the center and corner of the concrete structure respectively. It gives general understanding on the interface behavior for the kind of structural systems under consideration that the separation is primarily related to the response of the intermediate column, while the sliding is caused by stress concentration resulting from the nonlinear behavior at the interface. It may be concluded that the sliding and separation can significantly influence the seismic response of soil-structure interaction systems and they should never be neglected in the seismic evaluation of existing structures as well as in the seismic design of new structures.



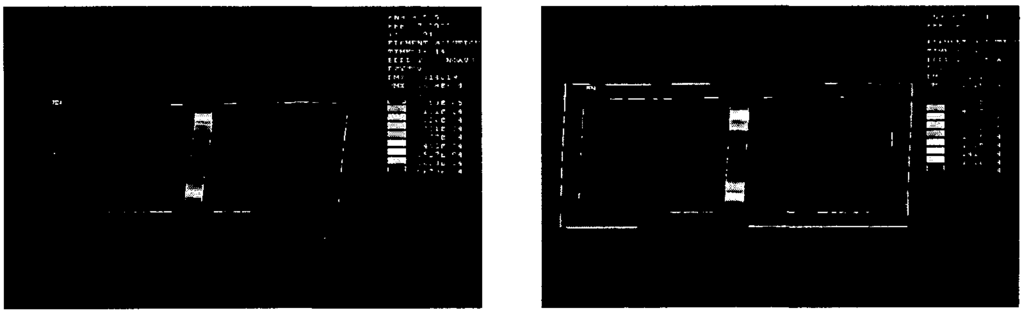
(a) material nonlinearity only (b) material and interface nonlinearities

Fig. 8. Comparison of normal stresses in concrete structure



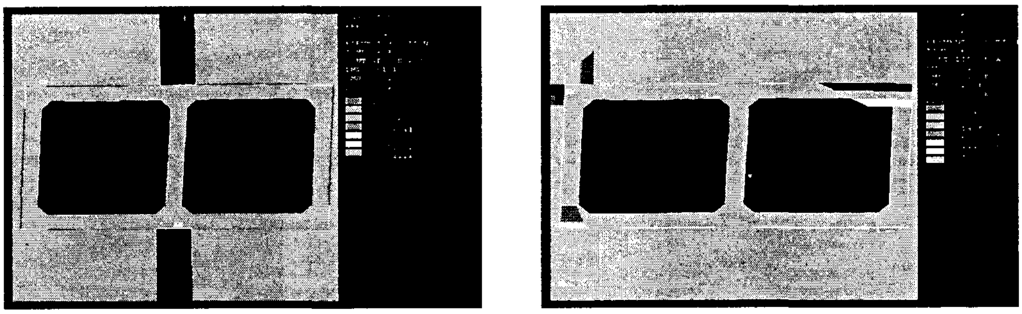
(a) material nonlinearity only (b) material and interface nonlinearities

Fig. 9. Comparison of shear stresses in concrete structure



(a) material nonlinearity only (b) material and interface nonlinearities

Fig. 10. Comparison of plastic hinges in concrete structure



(a) separation status (b) sliding distances

Fig. 11. Separation status and sliding distance in concrete structure

6. CONCLUSIONS

The paper presents an effective analytical method for a realistic response analysis of SSI systems in which separation and/or sliding can take place at the soil-structure interface and the structure manifests material nonlinear. The proposed method is applied to dynamic analysis of a 2-D underground box structure subjected to a strong earthquake. The numerical results suggest that the sliding and separation at the interface can make a significant effect on the seismic performance of underground box structures and should never be neglected.

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